

# Seismic Energy of Small Earthquakes

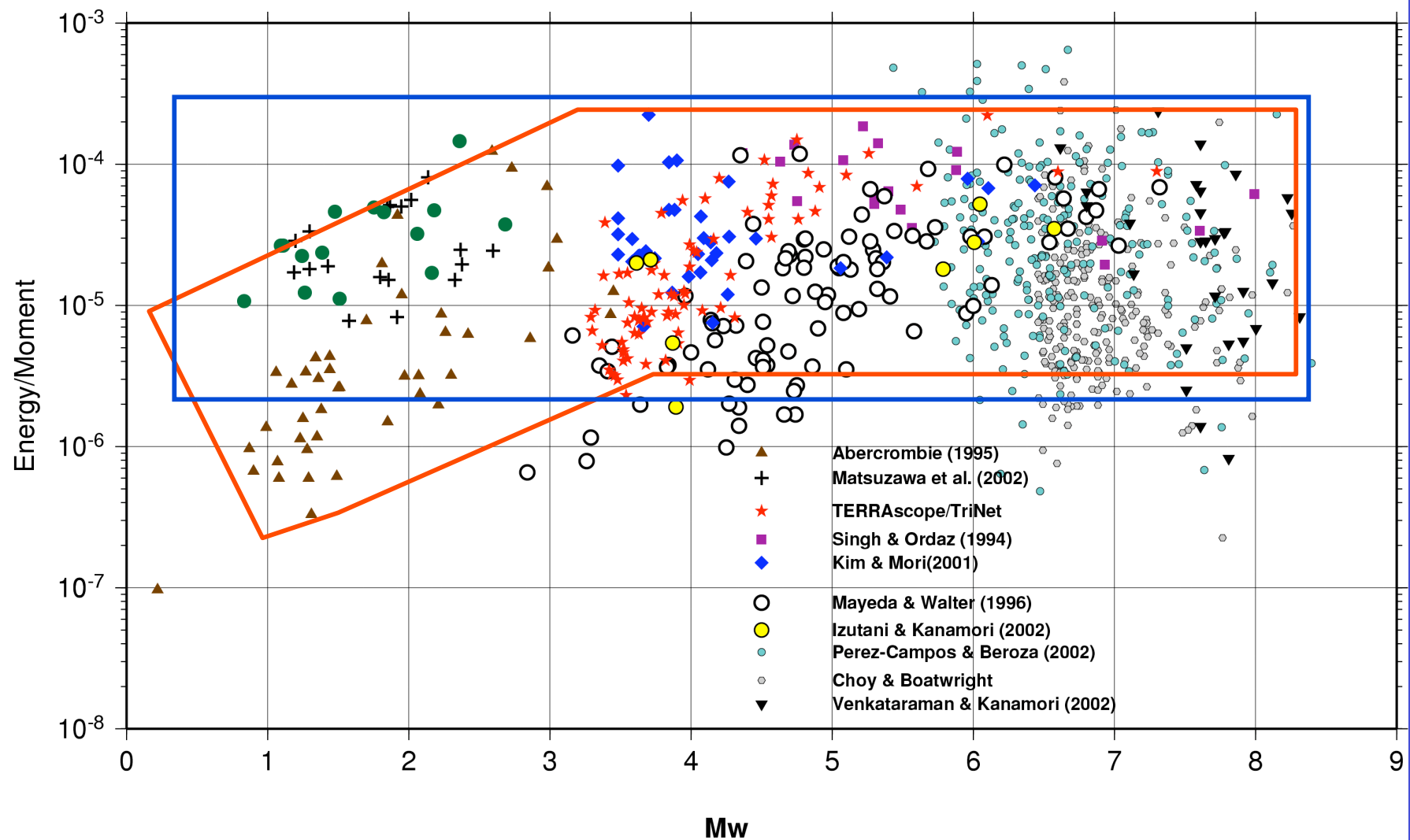
Anupama Venkataraman  
Gregory C Beroza  
Satoshi Ide

# Why are seismic energy estimates important?

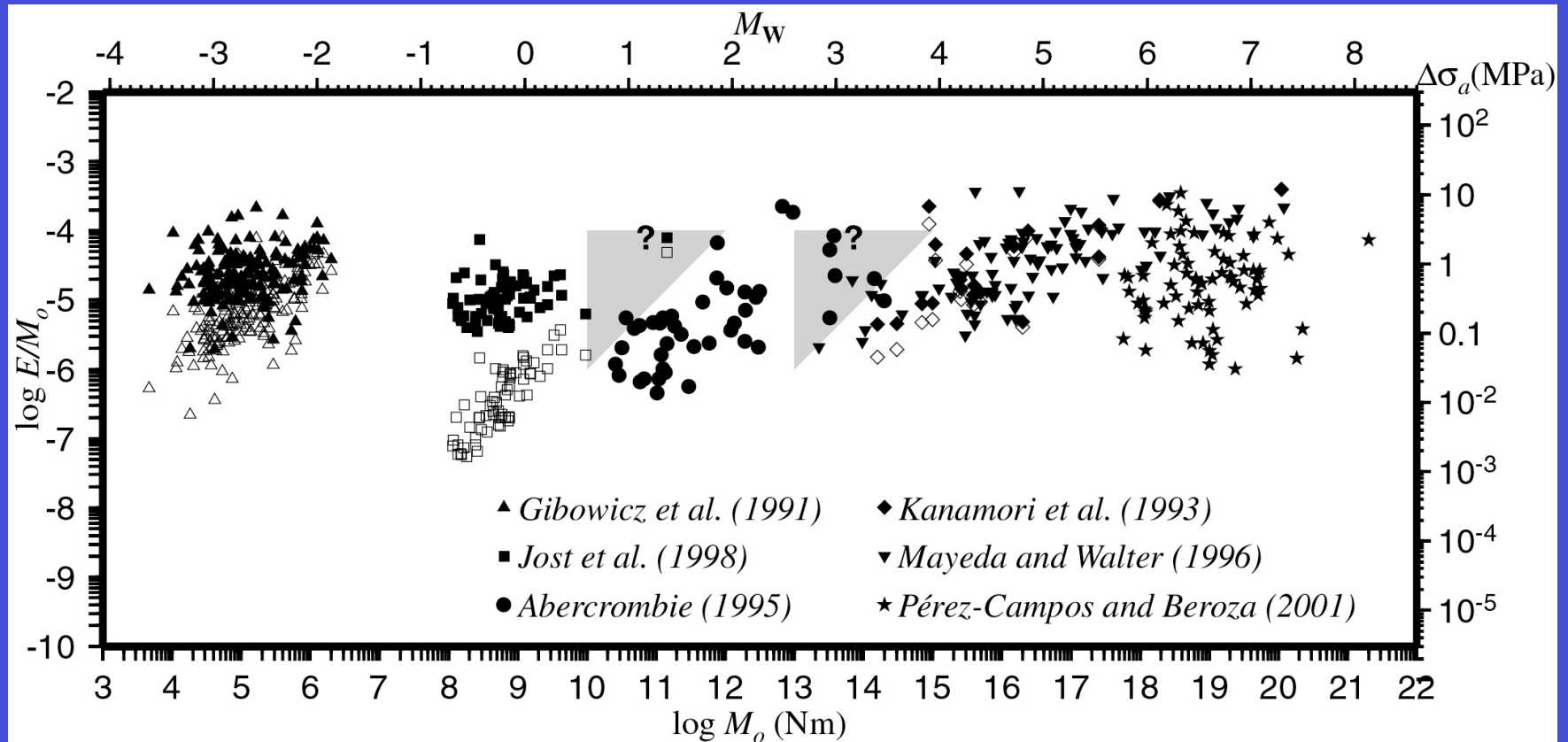
Insight into the physics of earthquakes

- Large earthquakes different from small ones?
- Differences between earthquakes in different tectonic environments?
- Variation in dynamics between events of similar magnitude?

# Breakdown in Scaling?



# Regional Energy Estimates - Problems



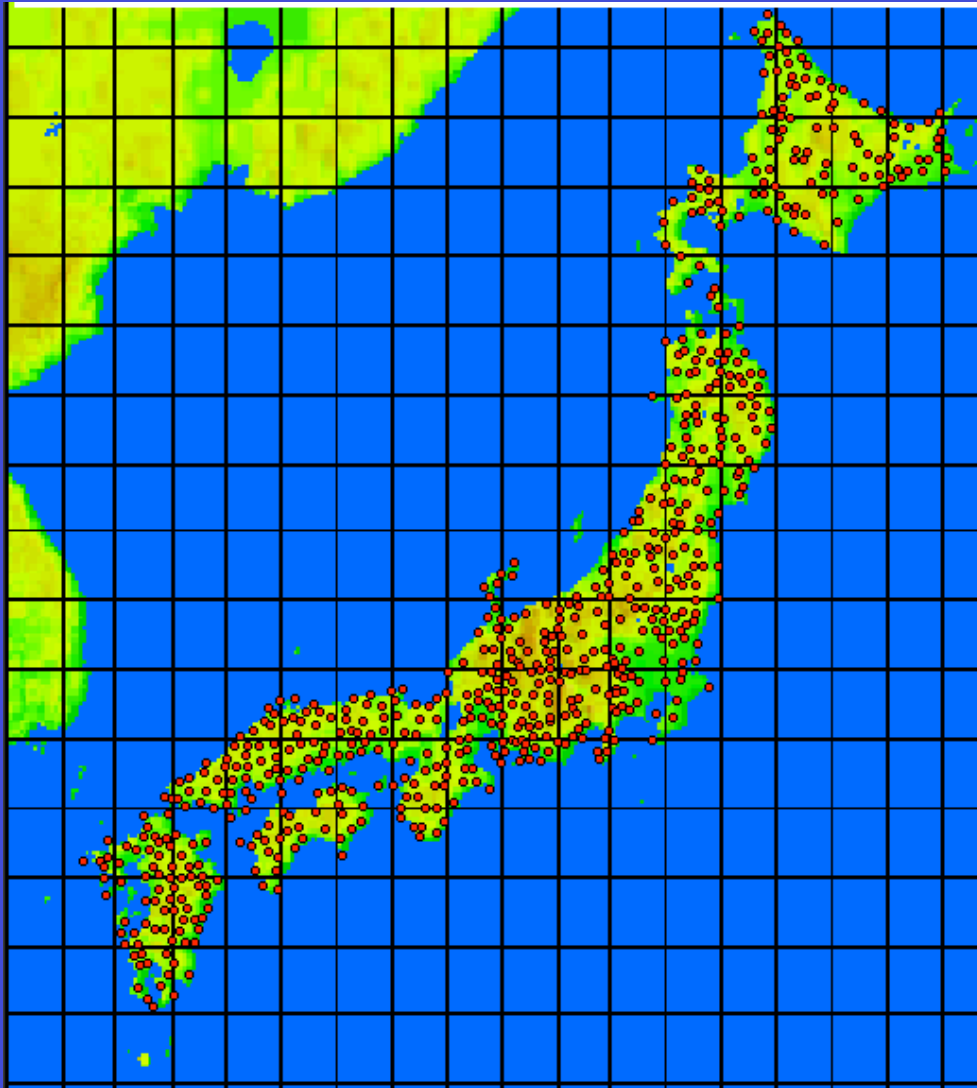
*Ide and Beroza, 2001*

- Problem: reliable path corrections over a wide bandwidth
- Solution: methods based on empirical Green's function deconvolution

# Small Earthquakes

- We require small earthquake records with high signal to noise ratio
- Surface data suffers from strong near surface attenuation; borehole seismometers?

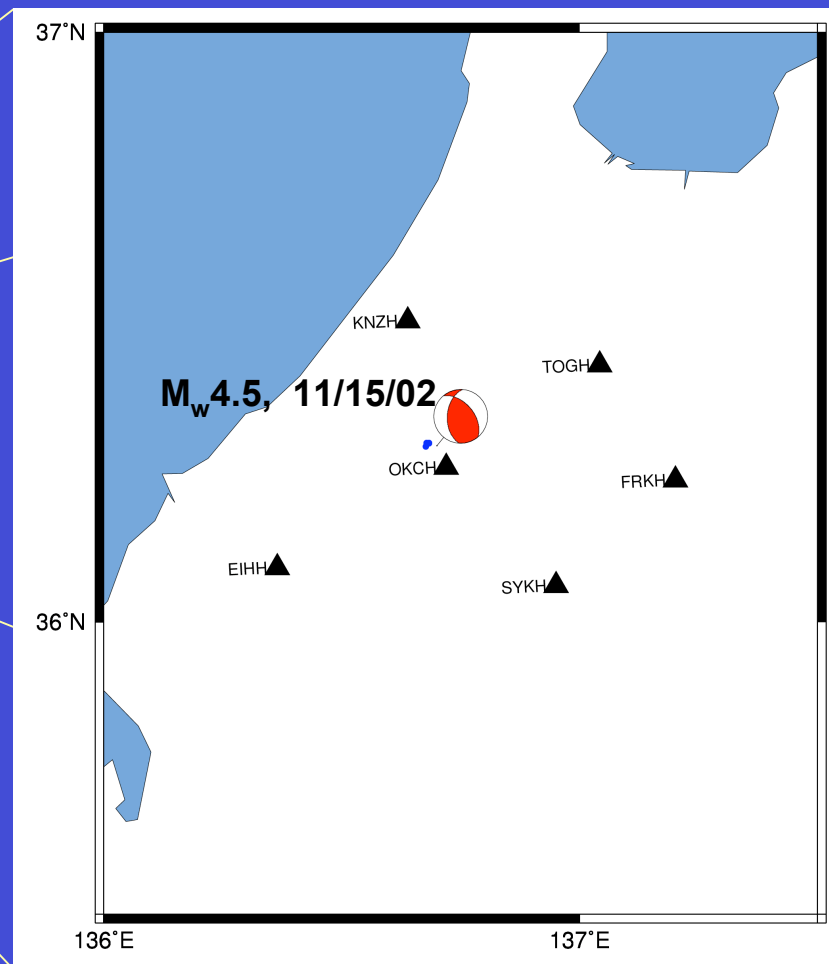
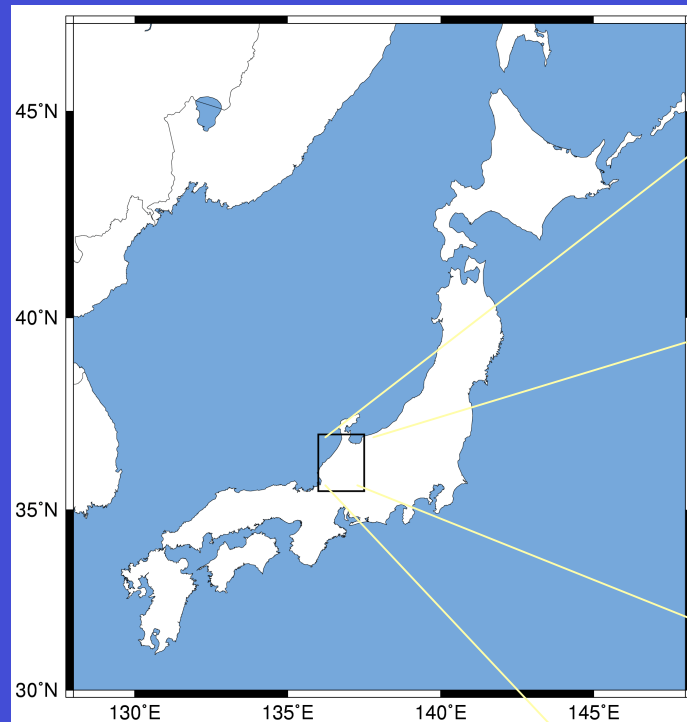
# Hi-net Station Distribution



- 559 borehole stations
- Depth Range: 100-200m,  
few > 1000m
- 1Hz velocity sensors
- High signal to noise ratio

<http://www.kik.bosai.go.jp/>

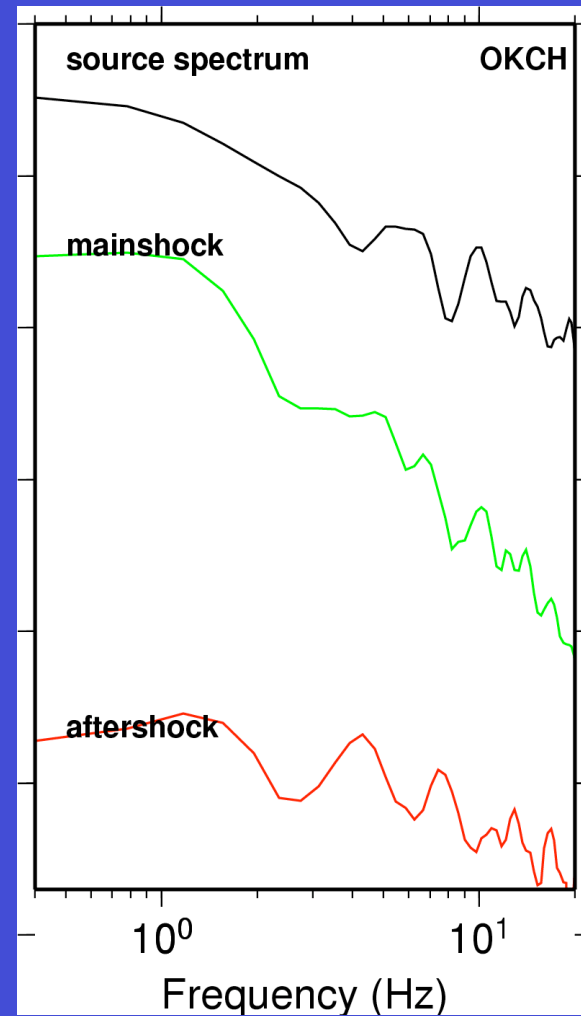
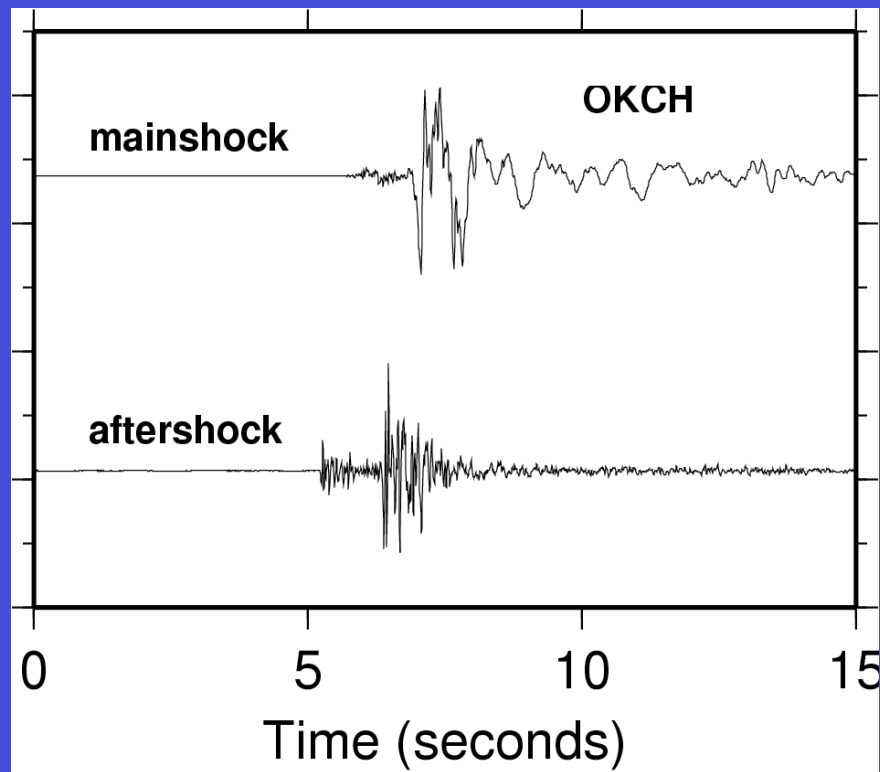
# Location Map



# Regional Data

- Hi-net data recorded by downhole velocity sensors (~100m depth)
- Mainshock ~ 4.5 (NIED)
- 6 EGF events magnitude ~ 2.5-3.7
- Data at 6 stations at distances between 6km and 50km

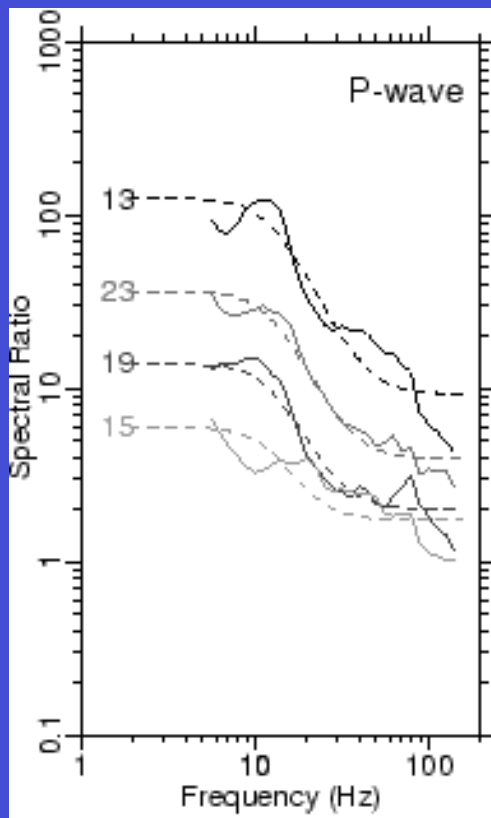
# EGF Method



# Limitations of the EGF Method

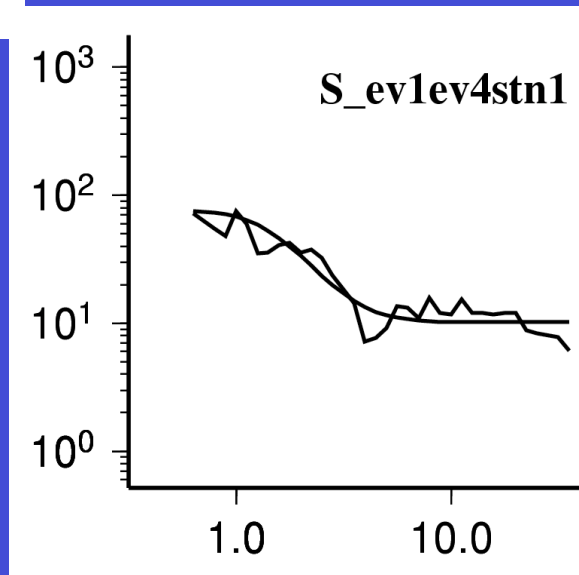
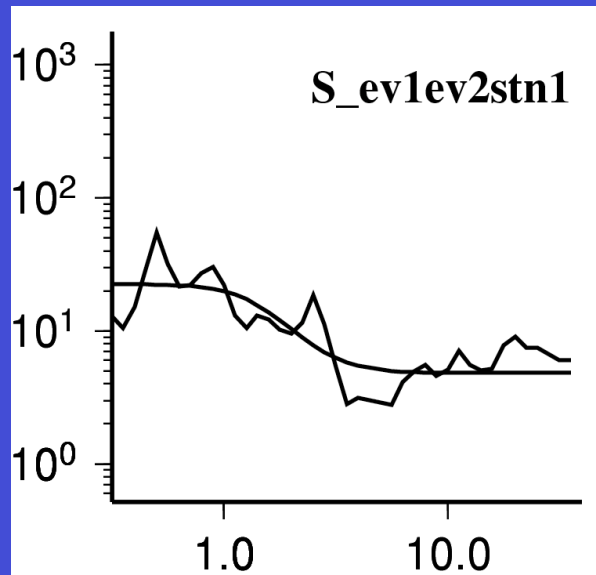
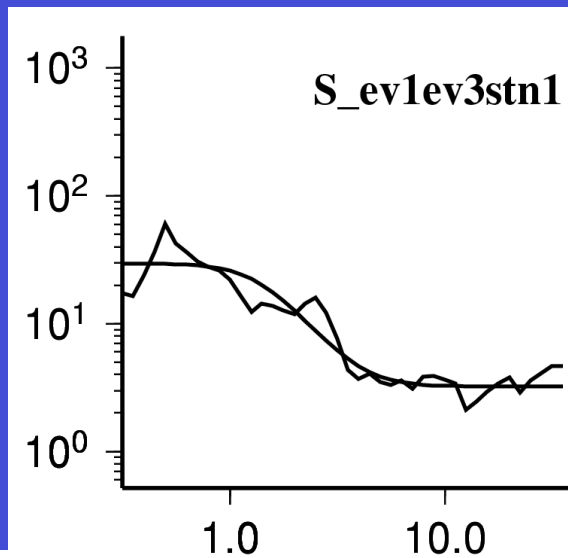
- Require aftershocks with magnitude at least two units smaller than the mainshock
- Cannot be used for small events, EGF data quality poor

# Multiple EGF (MEGF) Method



- Take spectral ratios of all event pairs
- Fit the spectra to determine the relative moments and corner frequencies

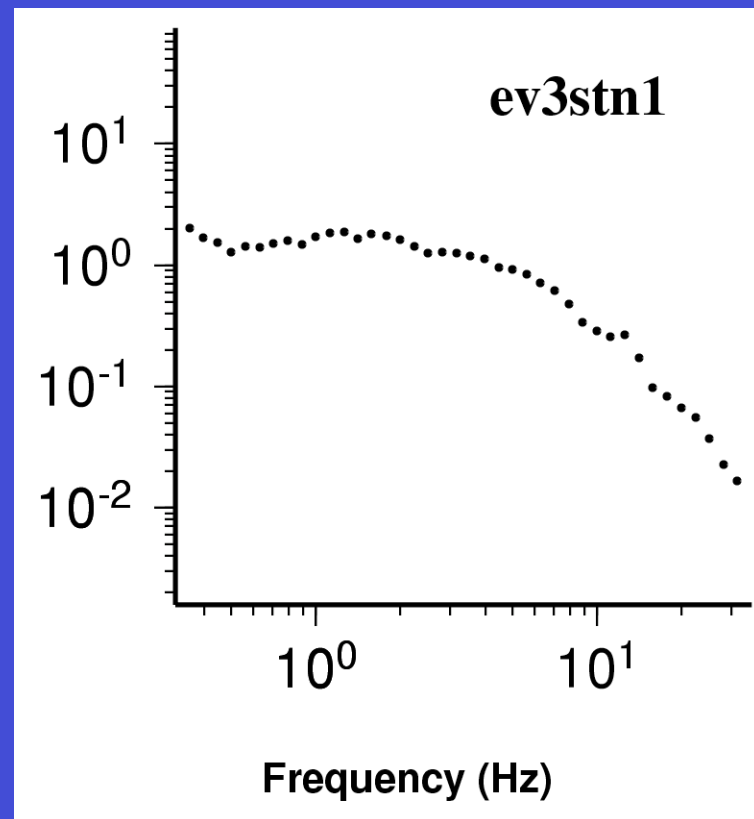
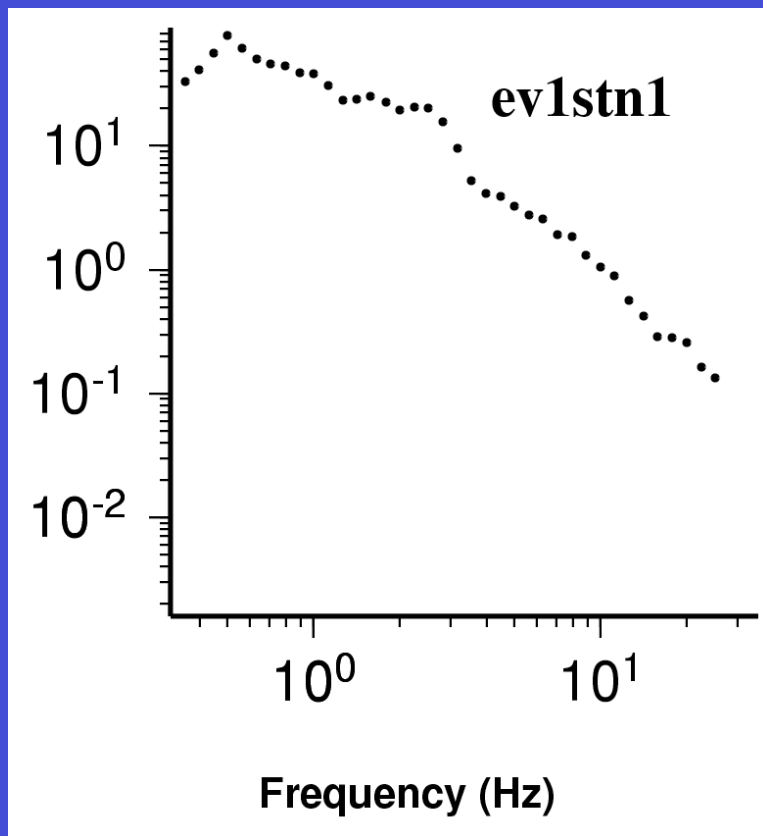
# MEGF method (Hi-net data)



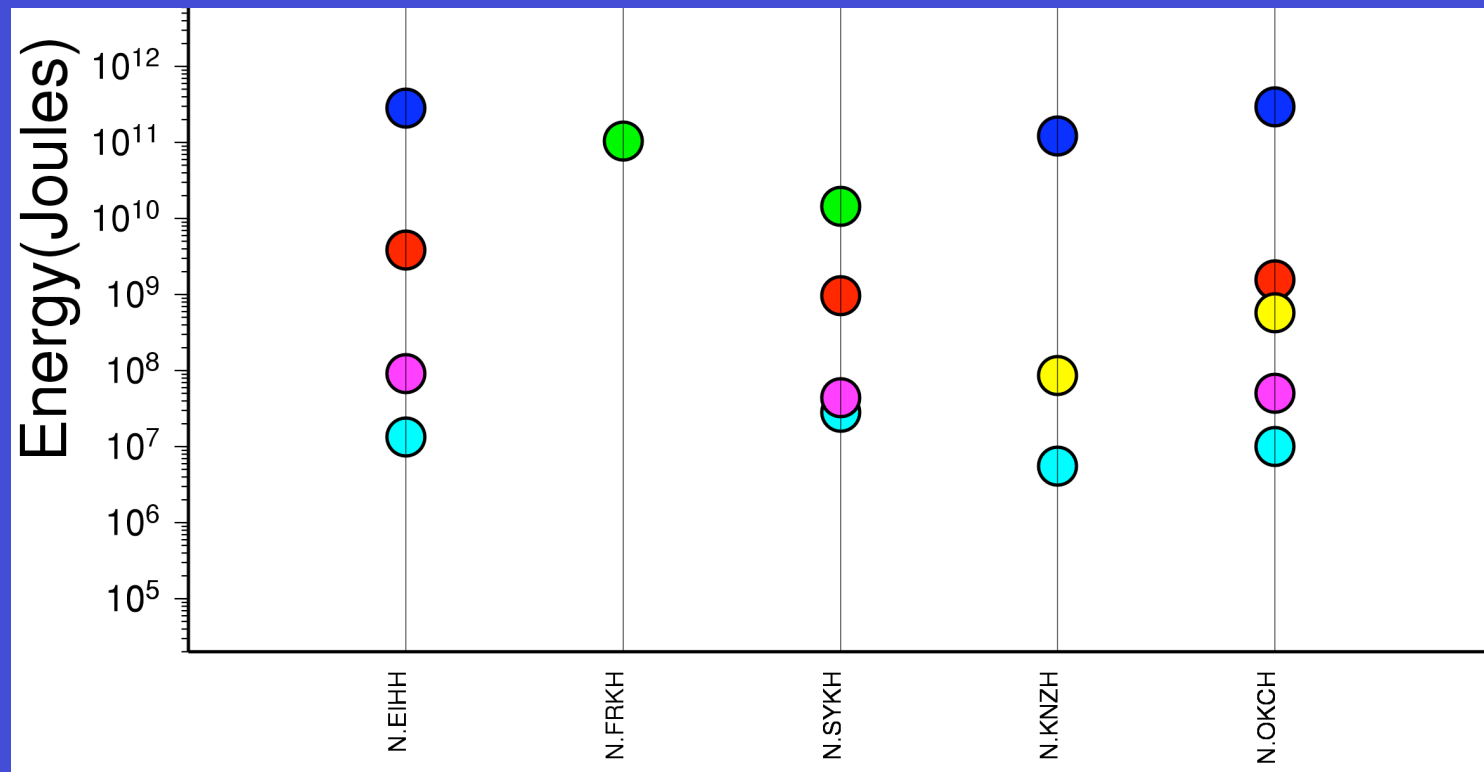
# MEGF Method (cont...)

- Determine the average propagation path effect to each station
- Determine the source spectra at each station
- Calculate energy from source spectrum

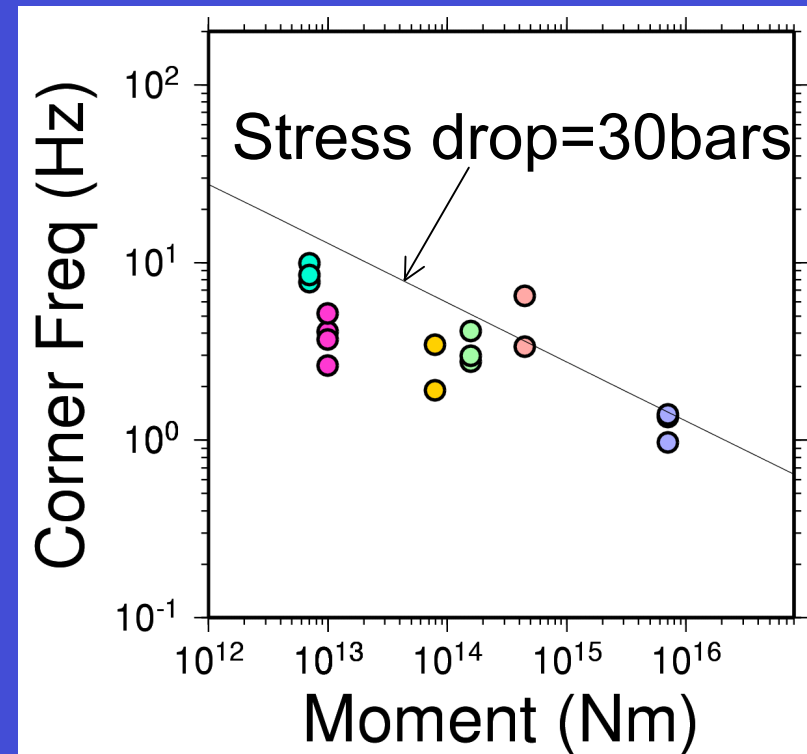
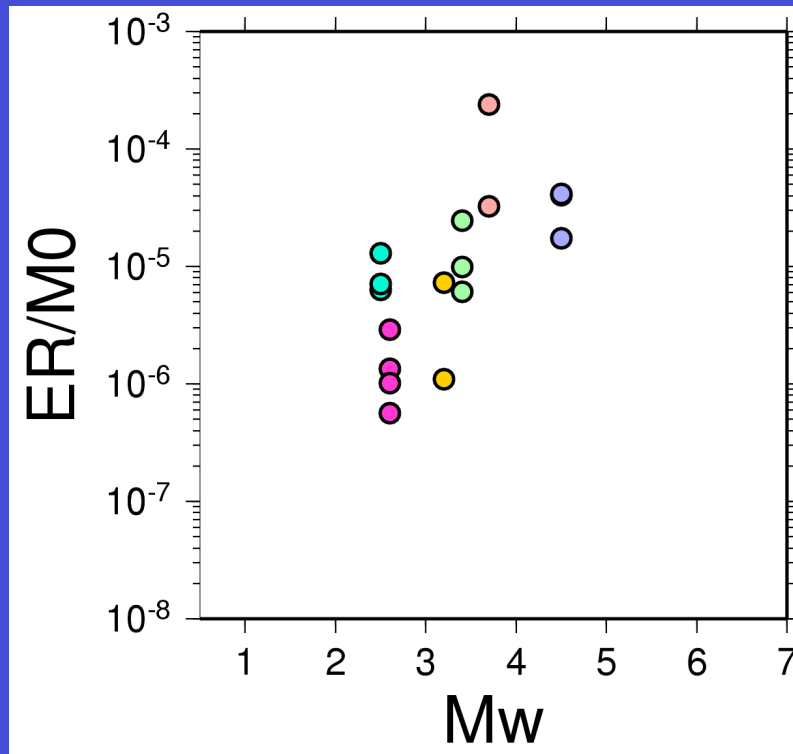
# Source spectra for two events obtained using the MEGF method



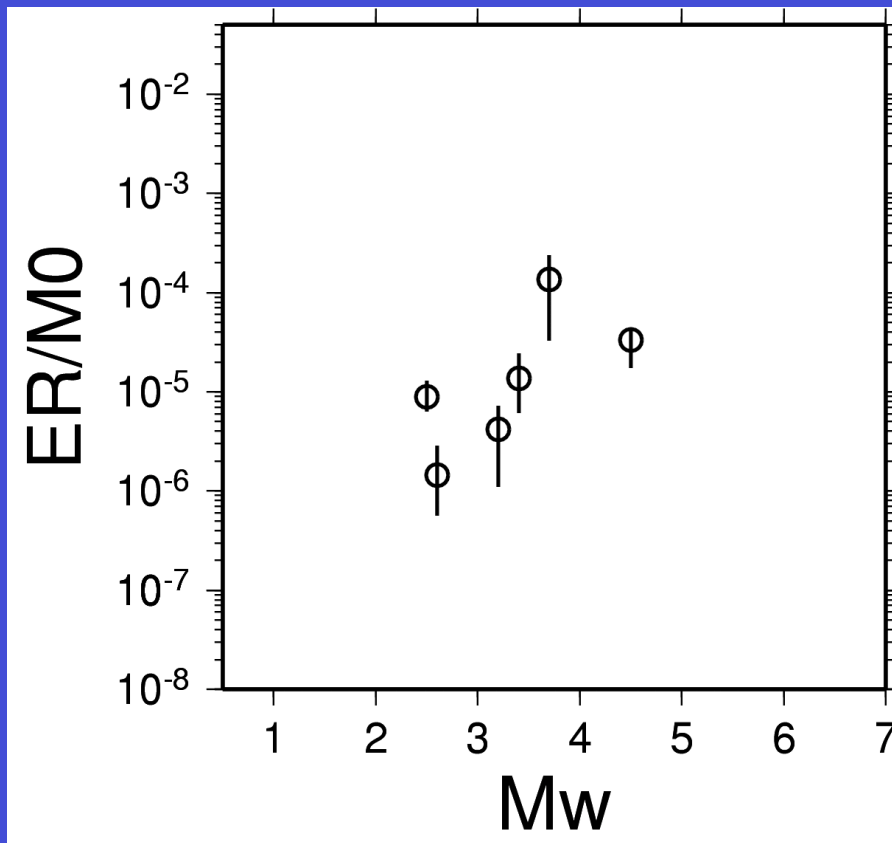
# Energy Estimates Using MEGF Method



# Energy and corner frequency variations

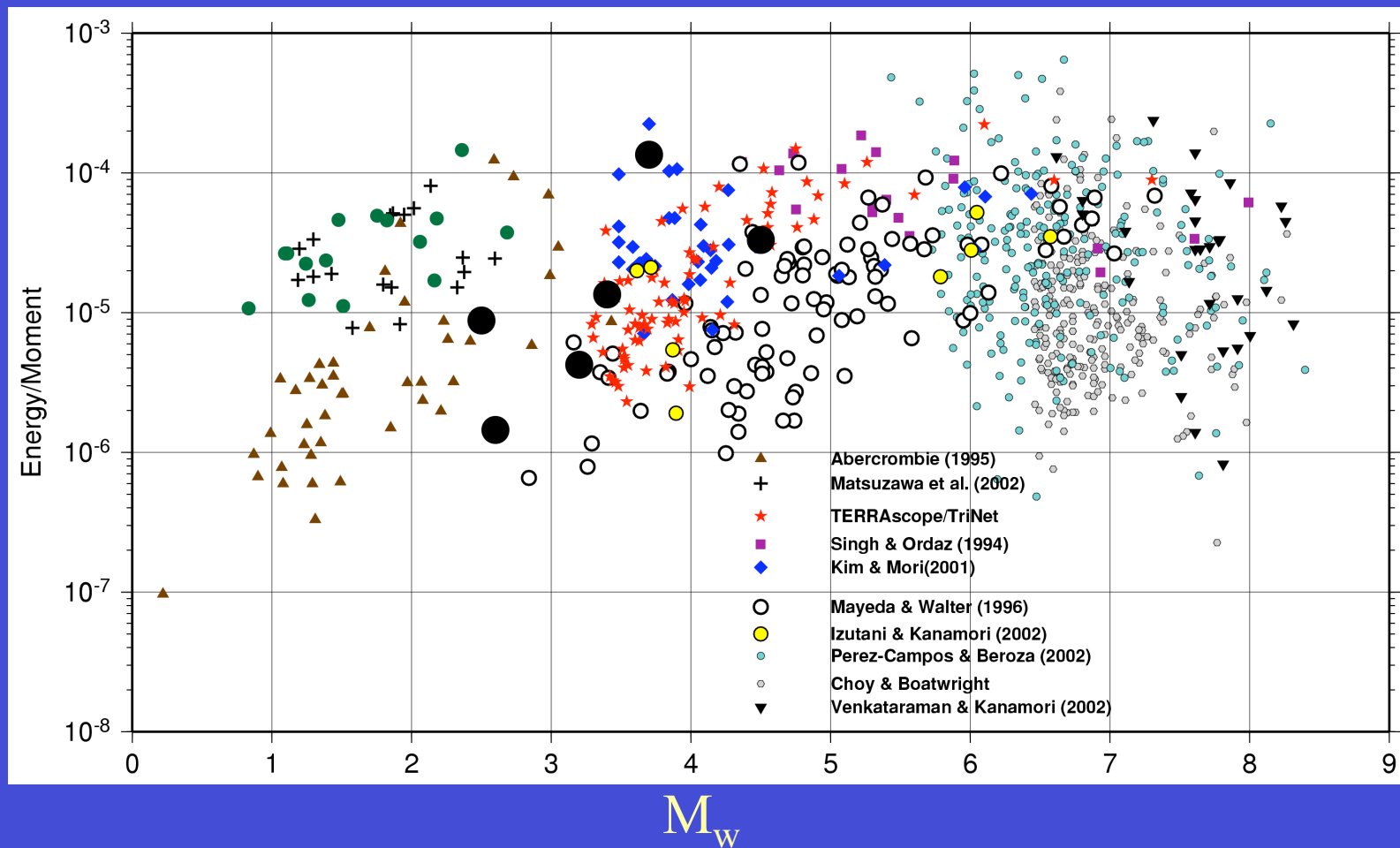


# Average energy estimates

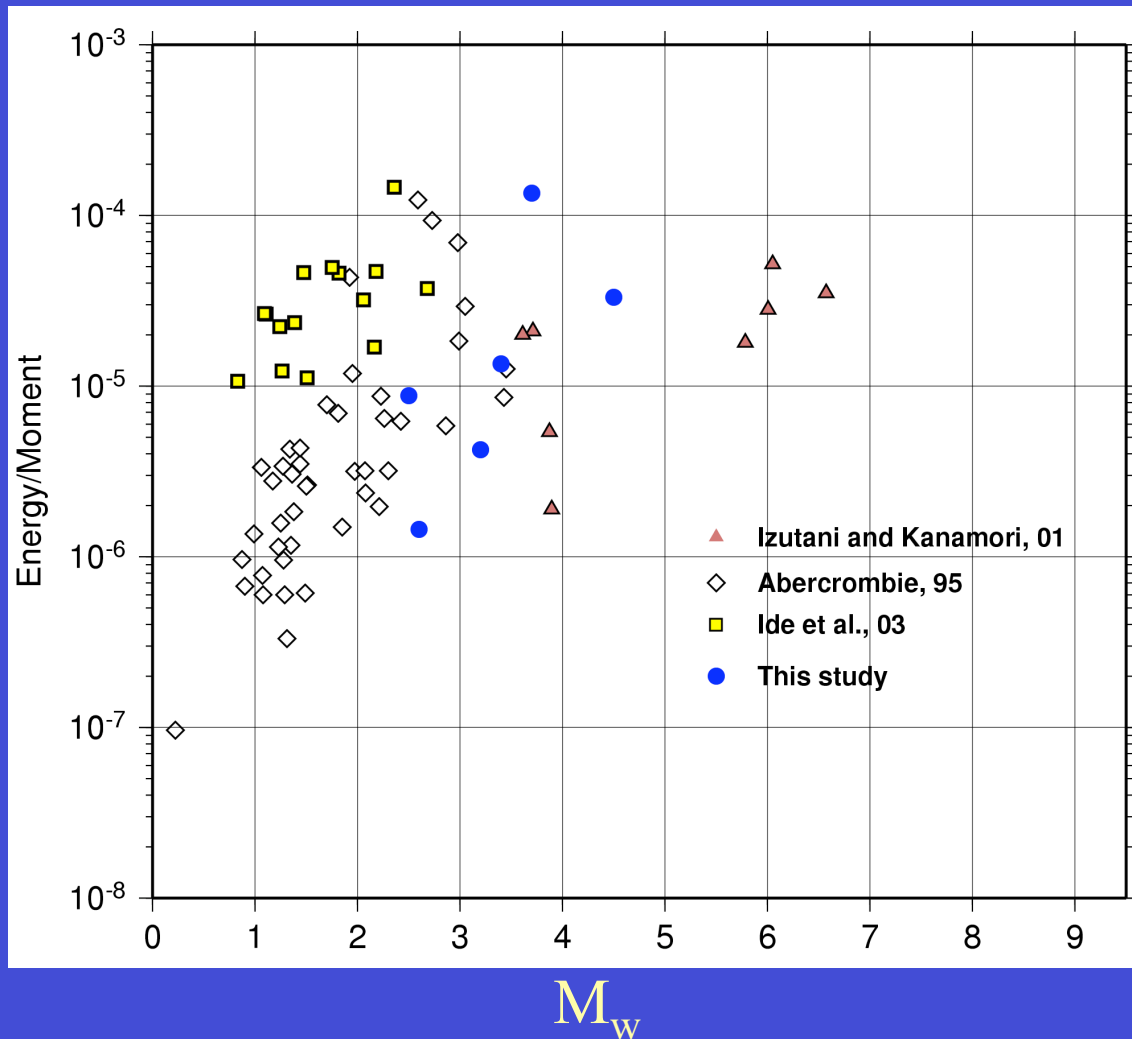


- Directivity
- Fall-off with size?

# Energy to moment ratio



# Energy to moment ratio – regional data



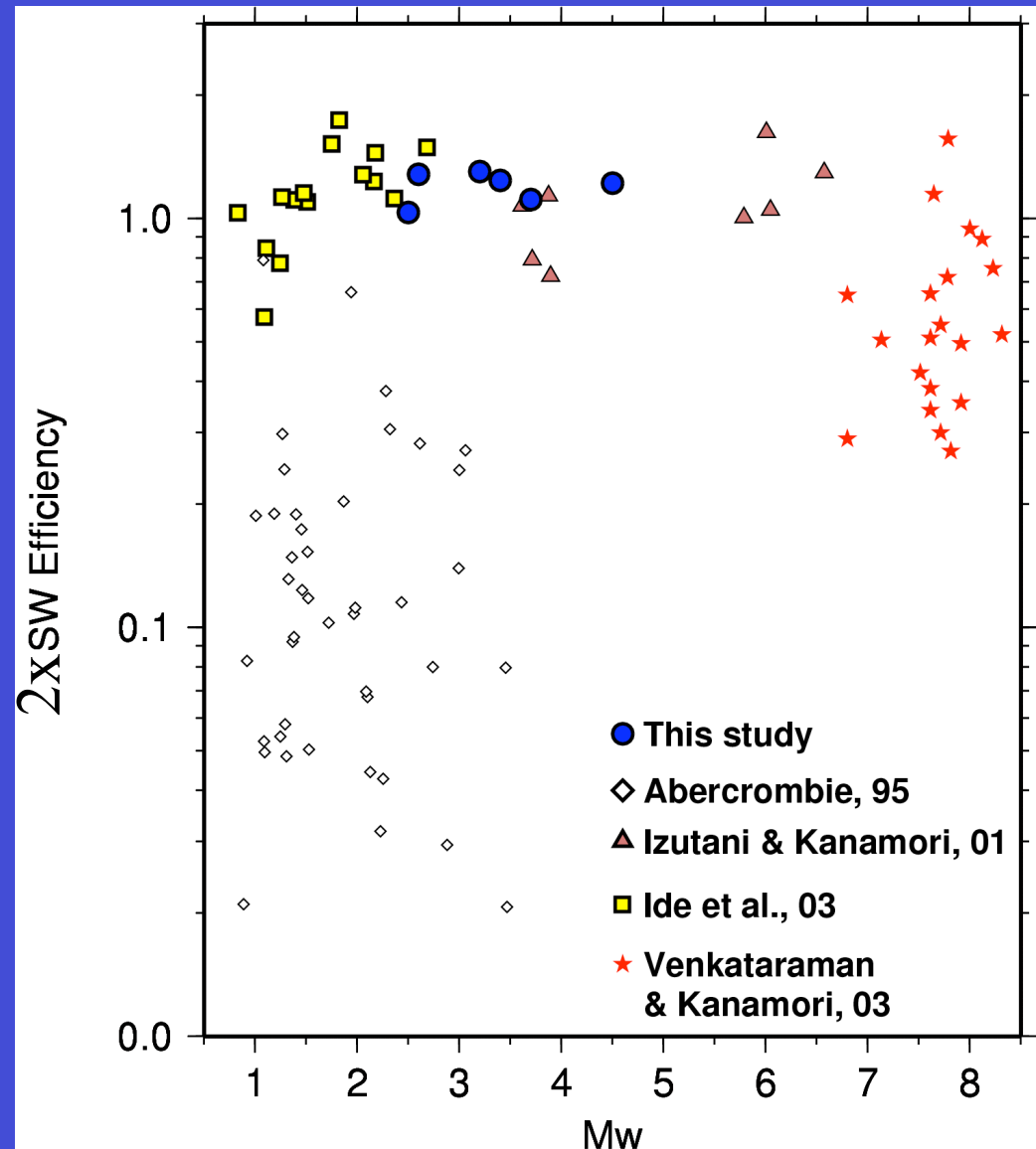
# SW Efficiency

$$\zeta_{SW} = i \frac{E_R / M_0}{\Delta \sigma_s} = \frac{\sigma_a}{\Delta \sigma_s}$$

Static Stress Drop,

$$\Delta \sigma_s = (\sigma_0 - \sigma_1)$$

SW Efficiency > 0.1  
Gibowicz et al., 1991  
KTB Data, 1998  
(not shown above)



# Partitioning of Energy in Earthquakes

$$\text{Radiation Efficiency, } \zeta_R = \frac{E_R}{E_R + E_G}$$

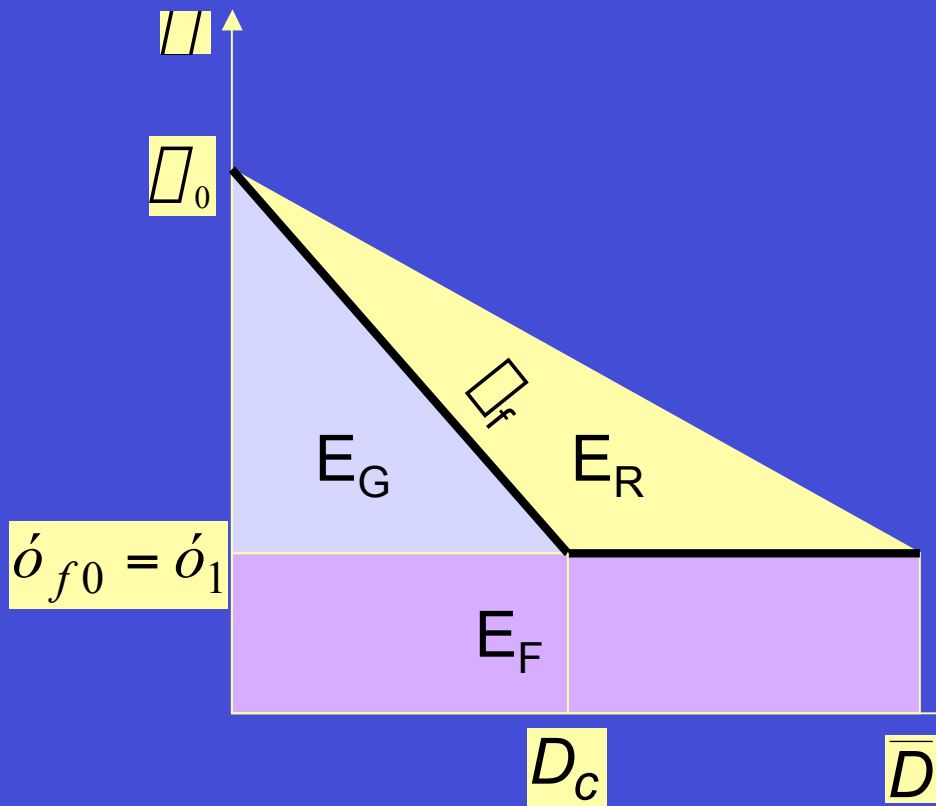
$$\text{SW Efficiency, } \zeta_{SW} = \frac{i E_R / M_0}{\Delta \phi_s}$$

$$\frac{\zeta_{SW}}{\zeta_R} = \frac{1}{2} + \frac{(\phi_1 - \phi_{f0})}{\Delta \phi_s}$$

$$> \frac{1}{2}, \text{ undershoot}$$

$$< \frac{1}{2}, \text{ overshoot}$$

$$= \frac{1}{2}$$



# Relation to Rupture Velocity

Radiation Efficiency,

$$\zeta_R = 1 - g(V)$$

Mode I:

$$g(V) = (1 - V / c_R)$$

Mode II:

$$g(V) = (1 - V / c_R) \sqrt{(1 - V / c_S)}$$

Mode III:

$$g(V) = \sqrt{\frac{(1 - V / c_S)}{(1 + V / c_S)}}$$

# Are the small SW efficiencies reasonable?

$$V/c_S = 0.8 \quad \zeta_R = 0.67$$

$$\zeta_{SW} = 0.1$$

$\zeta_{SW} < \zeta_R$   $\square$  stress overshoot  
overshoot required  $\sim 42\%$

$$V/c_S = 0.8 \quad \zeta_R = 0.67$$

maximum stress overshoot = 0.35

$$\min \zeta_{SW} = 0.10$$

- 1) Can stress overshoot be so large?
- 2) If not, how do we explain the small efficiencies?

# Conclusions

- Energy estimates have become more reliable
- MEGF method can be used to calculate energy for small earthquakes
- Require multiple-recording, deep borehole, broadband data
- Examine the variation in energy to moment ratio as a function of stress drop to understand the physics of the rupture process